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Scientific Controversies in Teaching Science: The Case of Volta

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Abstract. This paper discusses a way of introducing a scientific controversy, which emphasizes objective aspects of such issues as multiple theoretical interpretation of phenomena, choosing a theory, insistence on the chosen theory, and others. The goal is to give students a better insight into the workings of science and provide guidelines for building theories in their own research.

1. Introduction

An in-depth discussion of scientific controversies in the classroom is one of the best ways to utilize the limited time teachers can spare for using the history of science in teaching science. Following a scientific debate can improve students' understanding of the inner workings of science, in particular, an introduction of a new scientific theory and its relation to experiment. Showing scientific results as debatable issues makes science more similar to other human activities that are easier to comprehend, such as a political debate or a court proceedings, which may sparkle an interest in science in some students. Finally, there is a pragmatic aspect in it as well: looking from different perspectives at a scientific concept can facilitate its understanding.

In this paper, I will focus on some aspects of the relationship between theory and experiment that have not yet attracted much attention. While discussing in the classroom why one theory replaces another, teachers usually emphasize that the new theory explains phenomena (experiments) unexplained in the old theory. The presumption behind this is that certain experiments naturally support one theory and contradict others. For instance, a teacher states that phenomena of interference and diffraction *prove* the wave nature of light and contradict the corpuscular theory. This statement, however, ignores the fact that throughout the eighteenth century these phenomena have been considered a strong argument *against* the wave theory of light (Kipnis 1992, pp. 193, 216). Apparently, the presumption mentioned above is nothing but a myth, and the true relationship between a theory and its experimental foundation is more complicated.

The best way to counter this myth is by showing how the same experiment gives rise to different theories. An excellent opportunity for such a study can be

found in two controversies associated with Alessandro Volta (1749–1827), Physics Professor at the University of Pavia: the debate on the "animal" electricity and the debate on the nature of the voltaic pile. First, I will present the relevant historical materials. Then, I will analyze them looking for such features of an interaction between experiment and theory that are common to both cases. Finally, I will suggest several experiments for a reproduction in the classroom. These experiments can enhance students' interest in the debate also show the limitations of an experiment as an argument in a scientific controversy.

2. The Story

2.1. THE "ANIMAL" ELECTRICITY

This controversy began in 1792 with the publication of the discovery by Luigi Galvani (1737–1798), Professor of Anatomy and Obstetrics at the University of Bologna. Like some other physiologists, Galvani believed that the "nervous fluid" responsible for animal movements was of an electric nature. This hypothesis was based on the existence of electric fish and a possibility of an electric stimulation of animals. After testing how a frog's muscle-nerve preparation reacted to static and atmospheric electricity, Galvani once noticed that a frog's leg contracted every time the muscle and the nerve were connected by a metal arc consisting of two different metals (Galvani 1791). To explain the new phenomena, later labelled "galvanic" or "galvanism," Galvani argued that the contractions occur when electricity flows between a nerve and a corresponding muscle through an external conductor, and that this electricity originates inside the frog. According to Galvani, this experiment (and some others) *proved* that electricity exists in every animal body, rather than being limited to electric fish. He had no hypothesis about its origin but offered one about its preservation: a nerve and a surrounding muscle make a sort of a Leyden jar that retains the charge until the nerve and the muscle are electrically connected. Galvani's arguments were based on experiments (Figure 1). To prove that the effect was due to an electricity of a new kind, he had to exclude other possible causes. First, he eliminated a possibility of a mechanical stimulation by laying down the nerve and the muscle on two metal plates and bringing the arc in touch with these plates rather than with the tissues: the contractions continued to occur. Also, he immersed the frog's feet in one glass of water and its crural nerve into another glass. When the arc touched the surface of water in both glasses, the legs contracted. Second, he proved the involvement of electricity by showing that if the connecting arc included a piece of a non-conducting material, such as glass or resin, there was no twitching. Third, he eliminated an involvement of static electricity coming from external bodies, by providing the arc with a glass handle and making the support for the frog from a conducting material. Finally, he excluded the role of atmospheric electricity by demonstrating that contractions continued when the frog's body was submerged in water. If the electricity involved, Galvani said, was neither static nor

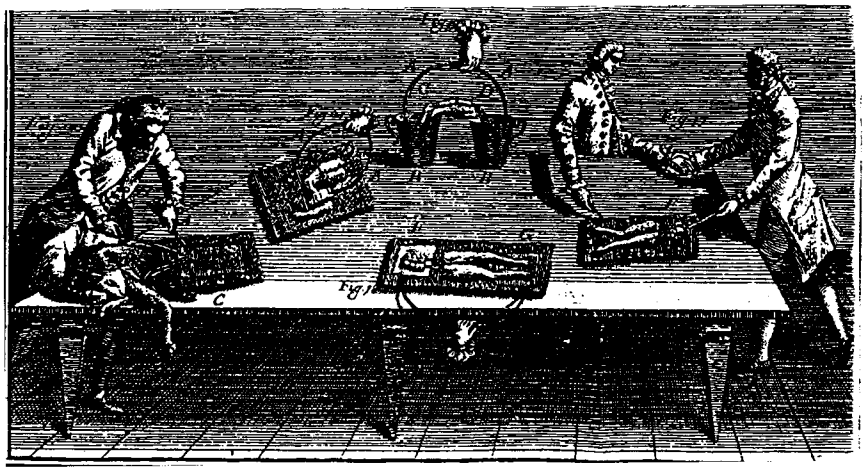

Figure 1. Galvani's experiments.

atmospheric, it had to be a new kind of electricity, and probably it was the "animal electricity."

2.2. THE "CONTACT" ELECTRICITY

There were some experimental results that Galvani could not account for, in particular, that convulsions were much stronger when the arc consisted of two different metals rather than a single one. This circumstance appeared crucial to Alessandro Volta (1745–1827), Professor of Physics at the University of Pavia. Volta agreed that the phenomenon was electrical but he assumed the main source of electricity to be outside, in the contact of different metals, and the frog merely being a conductor.

Being unable to explain the convulsions produced with a single metal, Volta maintained for a while the "animal" electricity together with his "contact" electricity (Volta 1793). Then in 1794 he discovered experimentally that a difference in temperature or polish at the ends of a wire was sufficient to excite contractions. Thus, he concluded, the contact electricity was sufficient to explain all phenomena, since if a single wire was heterogeneous, it could be considered as two different metals. Giovanni Aldini (1762–1834), Professor of Physics at the University of Bologna and Galvani's nephew, countered this argument with a new experiment. He showed that mercury free of the heterogeneity described by Volta did produce contractions, and so did charcoal (Aldini 1794). Another strong blow to Volta's theory came from Galvani's experiment in which contractions occurred when a nerve directly touched the muscle without any intermediaries.

First, Volta tried to find a flaw in the opponents' experiments, such as mechanical pressure or a chemical difference at the ends of the connecting arc, but eventually he decided to modify his own theory. Prior to that he maintained, on the basis of his experiments, that the simplest circuits to create the contact electri-

city consisted of two different conductors of the first class (metals and some other solids) and one conductor of the second class (liquid or a humid body), or of two different conductors of the second class and one of the first class. Now, he adds to these two a third variety: a circuit made of three different conductors of the second class (Volta 1797a). This modification was specifically designed to explain the "all-animal circuit", in which the conductors in question were the nerve, the muscle, and the animal fluids. Thus, the key of the new theory was that a contact of *any* two different substances is a mover of electricity.

Although Volta's new theory (let us call it the "universal contact") explained all galvanic phenomena, this generality was a sign of weakness rather than strength. Indeed, his statement that any three conductors of the second class created galvanic electricity could not be independently verified, for the only experiment supporting it – the "all-animal circuit" – was the one that the hypothesis was created to account for. Besides, Volta has a difficulty in combining this generality with the fact that the contractions produced by two different metals and a liquid were much stronger than the rest. Actually, he opened a path for returning to his original theory that weakest contractions may result from internal animal electricity while the stronger ones from the external electricity. At the time, no one utilized this opportunity, but fifty years later this theory began to gain strength.

By 1795, Volta realized that he could not fully establish the existence of the "contact" electricity without eliminating the "animal" electricity. The main difficulty with this was that the frog's preparation was the only available sensitive detector of galvanic electricity: one could always say that electricity responsible for the contractions came from the frog itself rather than from the external part of the circuit. For this reason both theories had about the same standing among scientists. The only way to prove that a contact of different substances creates electricity was to replace a frog by a non-animal electric sensor, and Volta decided to try Nicholson's doubler of electricity.

The doubler consists of a sensitive electrometer and three polished discs of the same diameter made of brass. One disk is set on top of the electrometer, its upper surface being covered with a thin layer of an insulating warnish (Figure 2). The second disk is placed on top of the first, it is warnished on both sides and provided with an insulating handle attached to its edge. The third disk, warnished on its bottom side sits on top of the second, it also has an insulating handle perpendicular to its plane. In the beginning, only two lower disks are in use so that the instrument works as a condenser electrometer: the source of electricity touches the underside of the first disk and the upper side of the second disk. Upon removing the source of electricity the second disk is lifted by the insulating handle. If the deviation of the electrometer is still small, the third disk held by its insulating handle is placed on the elevated second disk. After this a finger briefly touches the upper side of the third disk and the two are separated. Next, the third plate touches the underside of the first while the second sits on top of it. Now, upon finger touching the second plate with a finger and removing it after first removing the third plate, the amount of

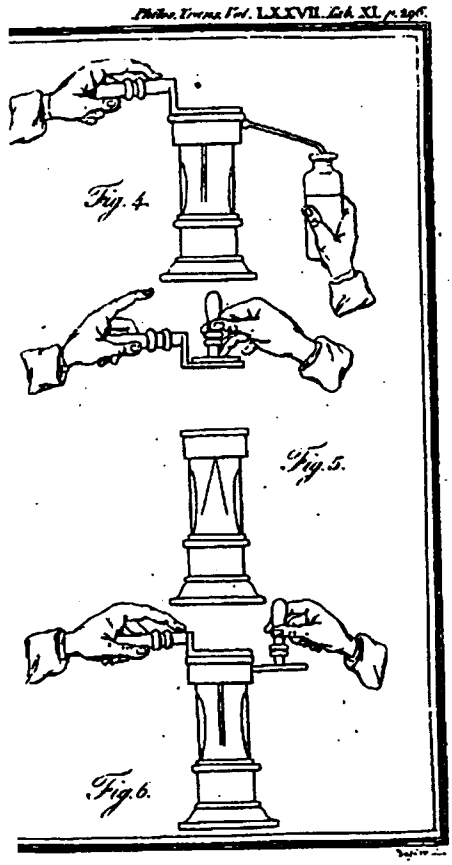

Figure 2. Bennet's doubler of electricity.

electricity on the electrometer is doubled. By repeating this procedure many times the amount of electricity can be considerably increased, which allows to measure very small charges.

Volta used a modification of the doubler invented by Cavallo, in which only the middle disk was mobile while others were fixed (Volta 1797b, c, d). He placed silver and tin rods on a wet cardboard, brought them in contact with two brass disks of the doubler and started the 'machine": after 20–30 turns the leaves of the electrometer diverged by 6 to 10 degrees. When he replaced the brass mobile disk with the tin disk and connected it a to brass rod while a brass disk touched a tin rod, the doubler showed a noticeable quantity of positive electricity. However, when he reversed the connections making each bar touching the disk of the same metal, there was no sign of electricity. Volta interpreted this result as a proof that electricity is created at the junction of different metals rather than that of a metal and a liquid (Volta 1797).

Volta was convinced that he found the decisive proof of the existence of the contact electricity, however other scientists were not so enthusiastic. The doubler was known for producing a "spontaneous" electricity during its work that was difficult to get rid of, which implied that while multiplying an extremely weak "signal" the instrument might have added to it an uncertain amount of "noise." Consequently, this experiment did not produce the effect on the scientific community Volta had expected. Galvani died in 1798 unconvinced, and Aldini continued to fight for his theory for many years to come. Volta was disappointed by such a resistance, for he considered his case clear and free of any flaws, because his theory of "universal contact" covered everything. Apparently, he saw no difficulty with the new experiment of Galvani in which contractions occurred when the nerves of two frogs touched one another (Pera 1992, p. 147). While to Galvani two nerves were similar substances, no one could prevent Volta from treating the nerves of different frogs as dissimilar. With no definition of "similarity" or "homogeneity" Volta applied this concept any way he wanted.

Regardless of its success in the debate, the theory of "contact" electricity led Volta to one of the greatest discoveries of the nineteenth century: an electric pile. More exactly, the theory that gave birth to the pile was the "two-metals contact" theory, while its "universal contact" modification never produced anything. While the pile diverted the attention of many away from the "animal" electricity, it brought to the fore another challenger – the chemical theory – which opened a new controversy.

2.3. THE "CHEMICAL" THEORY

This theory was initiated by Giovanni Fabbroni in 1792, but it became known only in 1797. According to Fabbroni, the primary cause of galvanic phenomena was chemical reactions rather than electricity. The basis for this theory was provided by an inability of electric theories to explain certain phenomena, in particular, why contractions occur even when the connecting circuit is open, or why the sensation of taste stimulated by a bimetal lasts after the bimetal is removed. Fabbroni experimented with different metals immersed in water and found that one of them oxidized, but only if the metals touched one another. This observation led him to the suggestion that the galvanic phenomena are due to an oxidation. Fabbroni did not try to eliminate electricity from galvanic phenomena altogether: he insisted that chemistry must have some role in them, in particular, in producing the sensations of taste or light. The "chemical" theory had a number of followers, including Alexander von Humboldt, however, it became really important only after the discovery of the electric pile when it redefined the role of chemical reactions in galvanic experiments from excluding electricity to being its cause.

2.4. THE PILE

The discovery became known after the publication of Volta's paper "On the electricity excited by the mere contact of conducting substances of different kinds" submitted to the Royal Society of London in April 1800 and read before the Society on June 26. The paper begins with a promise to inform of "some striking results I have obtained in pursuing my experiments on electricity excited by the mere mutual contact of different kinds of metal, and even by that of other conductors, also different from each other, either liquid or containing some liquid, to which they are properly indebted for their conducting power" (Volta 1800, PM, p. 289). This sentence already contains a complete theory of the phenomena to be described. By offering a theory up-front Volta implies that the purpose of the paper is not so much to get an additional support for this theory as to describe some remarkable phenomena he observed by means of a new apparatus. This apparatus consisted of many similar components, each of which included two different metals ("couples"), such as silver and zinc or copper and zinc, and a piece of cardboard or cloth moistened with pure or salt water. In one form of this apparatus (a "pile") all these components ("couples") made up a column arranged from the bottom up, for instance, as follows: copper, zinc, cloth, copper, zinc, cloth, etc. Another version of this apparatus, called a "chain of cups," consisted of a number of non-metal cups filled with salt water, each having a zinc and a copper plates immersed into water. The cups were arranged so that zinc of one cup was connected to copper of another cup, and so on (Figure 3).

Volta observed that when the number of couples was sufficiently high, the pile produced a shock similar to that of a Leyden jar. In addition to a shock, the apparatus could affect an electrometer and produce an electric spark, although these actions were less pronounced than the shock. For these reasons, Volta compares his apparatus (it became known later as "voltaic pile") to a battery of Leyden jars, "weakly charged" but of an "immense capacity." However, he emphasizes two important differences between them: (1) the pile acts continuously, providing repeating shocks without being recharged by an external electricity; and (2) it consists solely of conductors of electricity. Volta drew from this difference two consequences. One was that he discovered the first "perpetual" source of electricity. Another one, less known, was that he found an explanation of the torpedo fish.

The recurrent references to electric fish may appear intriguing to the reader viewing this paper in light of the debate about the existence of "animal" electricity, because the relevant experiments were carried out on frogs rather than torpedo. However, as Volta understood it, he had already refuted the "frog's electricity" in 1797, while electric fish remained a mystery. In fact, Volta never doubted that the shock produced by the torpedo was electrical, nor did he question that the electricity involved, unlike the case with frogs, resides inside the animal. His main argument with physiologists was that if electricity had any role in animal life, it could be explained by physical factors alone without bringing in any mysterious

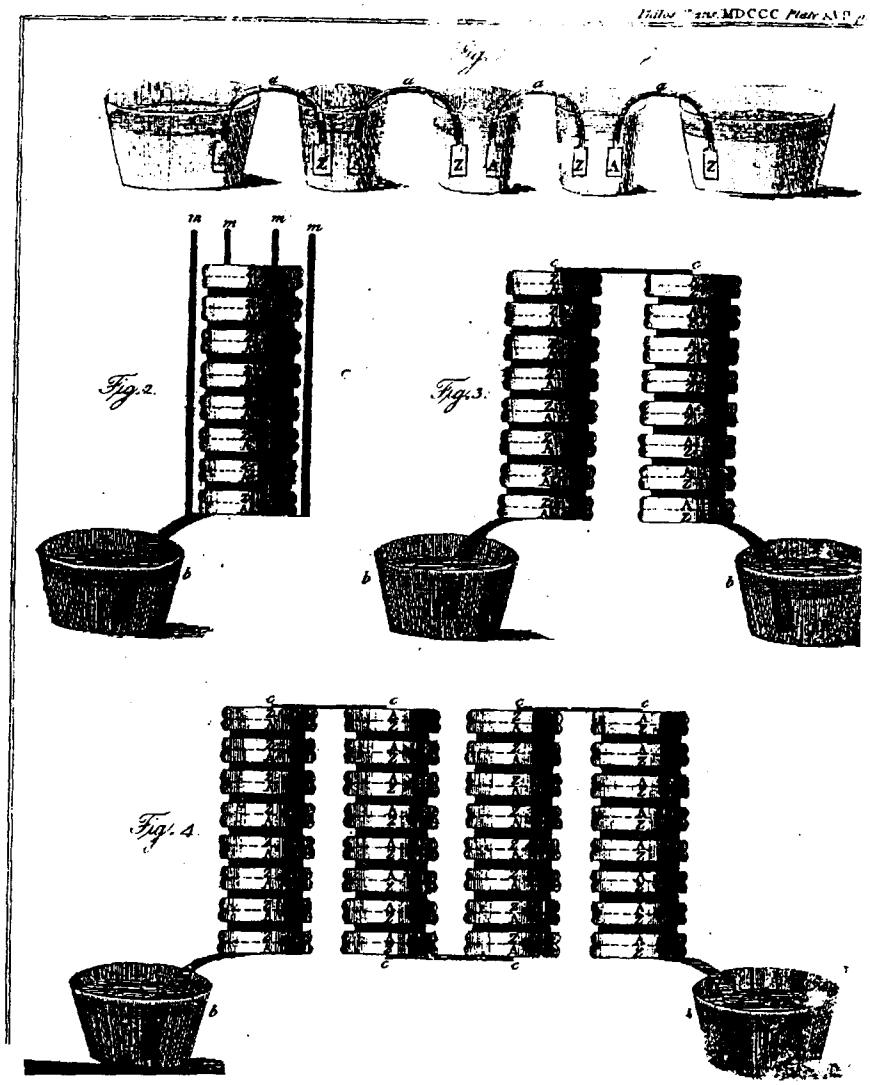

Figure 3. Volta's experiments.

"vital forces." As concerns frogs, he had already demonstrated – so he believed – that their contractions were due to an external "contact" electricity. In the case of the torpedo, however, his task was different: to conceive a physical model of its electric organ. Without fulfilling this task, Volta did not feel that his program of explaining life phenomena by physical processes was complete.

Volta begins with a critique of William Nicholson's theory of the electric organ of the torpedo, which compared it to a battery of Leyden jars. In Volta's view, since all membranes making up the columns of the electric organ are filled with fluids, they are comparatively good conductors. Since a Leyden jar cannot be made

without an insulator, Volta concluded that electricity produced by the torpedo and some other fish cannot be static electricity. On the other hand, his pile consisted solely of conductors, and this, Volta supposed, could be the necessary model: the electricity of fish is galvanic, being produced by a contact of organic substances of different nature. To support this theory he indicates that the shocks produced by his apparatus are comparable in strength to those of a languid torpedo, and that it can give repeating shocks. He even calls his apparatus an "artificial electric organ." This name, as well as the initial shape of the apparatus – a column – show that his preoccupation with imitating the electric organ of the torpedo was an essential element of his research program.

To convince his readers, Volta wants them to succeed in repeating his experiments. Thus, he explains in detail how to build the apparatus and how to use it. In particular, he recommends to increase the number of couples and wet the fingers touching a pile, or, better still, by immersing a part of the hand in water that is connected to the pile. These tips are more than empirical findings, they are closely correlated with his theory. Volta maintains that only a junction of two metals is an "electric motor," while the liquid itself is merely a conductor. Since one of the two metals attracts electricity stronger than the other, each couple moves electricity in a certain direction, e.g. from zinc to copper. Thus, if several couples have the same orientation, their efforts combine, and electricity moves faster: the more couples, the better. As to wetting the hand connected to the pile, it is to reduce its resistance. Using the whole hand instead of fingers serves the same purpose by increasing the area of its contact with the liquid. This idea provides a fine opportunity for physics teachers to expand their teaching of resistance to non-metal conductors, especially because its meaning is not clear to some people even now (Mentens 1998, p. 309).[1]

Although Volta insisted that he does not need the pile to support his theory of contact electricity, it was the pile that made many scientists to turn to Volta's theory from that of Galvani. They reasoned as follows: (1) the actions of the pile are electrical; (2) since its effect is nothing else as a multiplied effect of a single couple, thus a contact of two different metals creates electricity; and (3) the electricity created by a bimetal is the same whether it is detected by an electrometer or by a frog, thus Galvani's experiments were due to the "contact electricity" rather than "animal electricity." In fact, the last conclusion was not logical, since a circuit with a frog could have had both sources of electricity, but this detail went unnoticed. Likewise, few people noticed that they had begun using the term "galvanic" ("galvanic circuit,' "galvanic current," etc.) to refer to phenomena produced by a voltaic pile rather than to those involving frogs (Kipnis 1987, p. 135). Yet, while securing Volta's victory over Galvani and Aldini, the pile brought to life even more powerful objections to his theory than before.

2.5. THE CHICKEN-AND-EGG PROBLEM

The first objections came from England. Having seen the first part of Volta's paper before it was read in full at the Royal Society on June 26, 1800, several scientists constructed voltaic piles and began experimenting with them. In addition to the effects described by Volta, they found that a pile can produce various chemical phenomena. In particular, Anthony Carlisle and William Nicholson observed the release of oxygen and hydrogen, which they attributed to decomposition of water, and also an oxidation of metals, while William Cruickshank precipitated a number of metals. A few months later, on the basis of these and other experiments, William Hyde Wollaston (1766–1828) and Humphrey Davy (1778–1829) suggested that, contrary to Volta's opinion, liquids play an active role in galvanic phenomena, and chemical reactions may be the cause of electricity rather than its consequence (Wollaston 1800). To show the active role of the liquid Davy performed the following experiment (Davy 1800). In an iron-copper pile with water, iron is charged positively, but if water is replaced with sulfate of potassium it changes its electrization to negative. He also created a pile of a single metal but of two different liquids: metal, cloth wetted with nitric acid, cloth with water, cloth with sulfate of potassium, same metal, nitric acid, etc. The acid and the alkaline at the ends of the pile were connected by paper strips moistened with water. When the metal was replaced by charcoal the pile worked too.

In his first responses to this criticism, Volta insists that he had already proved the role of a contact of different metals as an "electric motor." He describes an experiment in which he held a zinc and a copper plates by insulating handles, touched them to one another, separated, and brought them in contact with the plates of a condenser electrometer. The leaves of the electrometer diverged by 1 to 2 degrees. Since no third wet object was involved, Volta concludes that the electricity is caused by a mere contact of two metals, without any chemical interaction.

Soon Volta changes his tactics claiming that the objections to his theory actually support it, including Davy's experiment with one metal and two liquids. In particular, he says, since a contact of any two different substances produces tension, and since the metal (or charcoal) is positive relative to one liquid and negative relative to the other, both tensions move electricity in the same direction. As to the role of chemical reactions, he observes that since adding salt to pure water does not change the tension or polarity, chemical reactions are of no consequence to producing electricity. Volta agrees however to give chemical reactions a role in improving the conductivity of the pile: when an acid, for instance, attacks a metal surface, it adheres closer to it than water and thus diminishes the resistance of this contact (Volta 1802).

The inconsistency of these two arguments is caused by Volta's usage of different detectors of electricity in the two cases. If the main criterion of the pile's power is tension as measured by an electrometer, then, indeed, different liquids produce about the same effect. However, when the power of a pile is measured by a shock or

the rate of a chemical reaction, both of which are derivatives of current, changing the liquid does change the outcome. In fact, Volta himself confirms this by noting that adding salt to water made the shock much stronger.

His second argument would have been unassailable, if he could provide an independent evidence that the conductivity of a liquid depends on the substance dissolved, its concentration, the area of contact, etc. However, for static electricity, such measurements were limited to comparing pure water with sea water. As to galvanic electricity, no such data existed at all. In fact, eventually it became clear that the only way to compare the conductivity of two piles made of the same number of couples was by comparing an effect that depends on current, such as a shock received by the same person. Thus, Volta had no ground to *assume* that given the same number of couples, the pile made of copper and zinc immersed into a weak sulfuric acid acts stronger than the one made of silver and zinc immersed in saline water, because the former pile has a greater conductivity than the latter.

Initially, Volta's theory of the pile had a considerable support, especially from Parisian physicists, but with time, especially since the 1830s, the chemical theory gained the upper ground. Interestingly, after 1802, Volta himself no longer participated in the debate.

3. Lessons from History

3.1. DEBATING THE TRUTH IN SCIENCE

A teacher should expect students to be surprised by the fact that scientists' behavior does not suit the image they have of a "scientific discussion," where the participants are attentive to the views of one another, passionless, and pursue no other goal as finding the truth. What they learn from the story, however, is quite different.

First, they see a rigid, uncompromising attitude, where each side claims to have the whole truth and insists on it until death. As shown above, there was some evidence that both "animal" and "contact" electricity exist. However, neither Galvani and Aldini, nor Volta were interested in a compromise. One finds this even more surprising when one remembers that Volta's first theory contained both sorts of electricity. Actually, instead of eliminating "animal electricity" Volta's last theory of the "universal contact" created a new model for it: electricity inside an animal originates at the contact of different tissues. Bearing this in mind, it would have been fair for him to say either in 1797 or in 1800: "There is no way I can disprove the existence of electricity inside an animal shown in the "all-animal circuit." But I can offer a better model of this electricity: animal electricity is produced not by "vital forces" which exist exclusively in animals but by a universal physical cause such as a contact of different tissues." This would have been perfectly consistent with his physical model of the electric organ of the torpedo. However, Volta never said this, and no one raised this sort of objections to his theory, at least not publicly.

Second, neither side was willing to reveal the shortcomings of one's own theory until forced to do so. Galvani knew that both muscles and nerves are conductors,

thus to preserve his Leyden-jar model he invented an oily substance that supposedly insulated the sciatic nerve from the muscle. Likewise, Volta could not have been unaware that his latest theory of the "universal contact" was unverifiable. Indeed, to test, for instance, that a contact of two different tissues creates the "contact" electricity one cannot use another frog's preparation as a detector, because the latter could generate the "animal" electricity. Nor can one employ an electrometer, since in this case the true source of electricity could be a contact of an animal tissue with a metal part of the instrument rather than a contact of two animal organs.

Third, while comparing a theory to experiment, its partisans emphasized only those aspects of an experiment that suited their theory. For instance, Volta preferred to measure the "power" (or "activity") of a voltaic pile by its tension, because tension does not depend on the chemical activity of the liquid. Davy, on the other hand, chose for that purpose the amount of gas released by the pile, because it depends on the liquid.

Fourth, when a logical connection between experiments and a theory was necessary but difficult to establish, a circular reasoning was called to help. For instance, to prove that the true "mover" of electricity is a contact of two different metals rather than that of a metal and a liquid, Volta carried out an experiment with dry zinc and copper plates connected to a condenser-electrometer. Whatever was the nature of the electricity he measured (probably it was static electricity), his conclusion that it was the same electricity he had obtained with the two metals touching animal tissues was unfounded. Such conclusion would be logical only if one *presumes* that the cause of the phenomena is solely in the metals, which is what one has to prove.

Finally, unlike the case of Galvani, in his debate with Davy, Volta does not offer any new experiments that could have shed new light on the matter. Apparently, he believes that his theory does not need an additional support, thus he focuses on counter-charges which could weaken the claims of the chemical theory. For instance, he questions the evidence that certain chemical reactions, such as oxidation, create electricity. Or, he attacks the usage of the shock as a gauge of a voltaic pile. In his view, "the electrometer is the best judge of the electric force, that is, it provides us with a more reliable and more exact measurement of this force than the commotion" (Volta 1802, p. 343). This change of his original position might have resulted from Volta's inability to explain why a shock produced by a pile does not depend on the size of its plates.

Without denying that the "human factor" affected somewhat the rhetoric of these controversies, there are details which do not fit the picture of a scientific debate as a purely social activity. Let us check the possibility of objective factors at work, by asking questions about the "deviations" from such a social discourse.

3.2. OBJECTIVE GROUNDS

The first question is: why did scientists divide for a long time between two theories instead of agreeing to embrace one of them? We see that in both cases each of the two competing theories was internally consistent, supported by experiment, and initially enjoyed about the same standing among scientists. If two theories appear to be equally legitimate, choosing one of them should be a matter of a personal choice, subject to various factors. For instance, we see an influence of professional interests, since physiologists primarily supported Galvani, physicists sided with Volta, and chemists preferred the "chemical theory."

The fact that the experimental results cited by each side did not contradict those of the opponents means that there was enough room for two theories. This was possible because the two theories focused on different aspects of the same complex phenomenon combining physiological and physical components. It was possible for Galvani to see the origin of electricity inside an animal and for Volta, outside it, because in most of these experiments both electricities were present: bio-potentials always exist in animal tissues, and employing metal conductors to connect them introduces electrochemical potentials. This was proven only around 1850, when the invention of depolarizing electrodes permitted scientists to separate the two electricities. While such technology did not exist at Galvani's time, still his experiment with the "all-animal circuit" should have warned against dismissing the idea of "animal" electricity too easily.

In the case of the pile, one could attribute the origin of electricity to a contact of two different metals (the "contact" electricity) with the liquid being a conductor, or to a contact of these metals with a liquid (the "chemical" electricity). As long as one considered the effect of the pile to be a multiplication of the effect of a single pair, it did not matter how the pair functioned. To account for a rise in a pile's ability to produce gas when a diluted acid replaced water, or with an increase of the size of its plates, one could say either that a greater chemical activity released more electricity at the contact, or that it improved electric conductivity: the difference was semantic, because the two concepts could not have been measured independently.

The second question is: why did not contenders try to reach a compromise? This appears to be quite possible in the case of Galvani and Volta because initially Volta accepted both "animal" and "contact" electricities. The main reason for him to eventually eliminate the former was adhering to the "Occam's razor", the principle of reducing the number of possible causes of phenomena to a minimum. As soon as he found that he could explain all galvanic phenomena by the "contact" electricity, he pronounced the concept of "animal" electricity unnecessary. Scientists had used "Occam's razor" frequently but not always successfully, and Volta was out of lack.

The third question is: why did each contender stubbornly adhere to a chosen theory ignoring its deficiencies? Since some defects of each theory were obvious to its defenders from its inception, apparently they decided to support it because of

the theory's *positive* contribution, with the hope that future research will resolve its difficulties and prove *their* theory to be the winner.

Thus, the behavior of Volta and his opponents in a debate was in part determined by impersonal factors that depended either on the phenomena under investigation or on common practices of scientists. It is quite clear, though, even from the materials presented above that personal factors were also involved, for some arguments of some participants suggest that winning an argument was no less important to them than finding the truth. However, this subject is beyond the scope of this paper.

4. The Experiments

These experiments are to be conducted in conjunction with the corresponding part of the story. To a large extent they may be open-ended. If a teacher wants to use these experiments to teach students the art of an investigation (Kipnis 1992), it is desirable to do them when students know only some of the historical results: in this way students will have an opportunity to compare their own results with those of Galvani or Volta. The experiments, especially those of Volta, allow many easily achievable modifications, and students are to be encouraged to be creative and devise new experiments to resolve the issue between Volta and Davy.

To give students a better feel of the original experiments, the emphasis here is on using the apparatus similar to the historical one and employing the original procedure. In the case of Volta, an electrometer had to be replaced with a voltmeter. Measuring current with a multimeter is a modern addition; however, lighting a bulb is a modification of a historical experiment of fusing a thin wire.

4.1. GALVANI'S EXPERIMENTS

If possible, do these experiments in a laboratory setting. Otherwise, the teacher should do them with students' help as a demonstration, making them visible to the whole class by means of a camcorder and a television set.

Materials: A frog's preparation (prepared not in front of students): it consists of hind legs and a part of the vertebra, from which sciatic nerves should be uncovered. Needle, electrostatic generator, a wire insulated at one end, strips of various metals (zinc, copper, aluminum, steel, etc.), insulated wires.

Procedure: First, demonstrate stimulation means known before Galvani: mechanical, static electricity, and chemical. Prick the nerve with a needle until a leg twitches. Take a metal rod with an insulating handle. Charge it from any source of static electricity and bring the metal in touch with the nerve or the muscle: you should see a brief contraction. Put a grain of salt on the nerve: the leg will start twitching.

Then show Galvani's experiments: (1) Touch the nerve with a zinc strip then touch the muscle with a copper strip: you should not have any reaction. Then bring the other ends of the metals into a contact: a contraction occurs. Try other pairs of metals, then try two strips of the same metal; (2) place a piece of aluminum foil under the nerve and another one under the muscle and touch them instead of the tissues: you should see contractions; (3) cover the top parts of zinc and copper strips with an insulating tape and repeat the procedure: you should see no twitching at all.

4.2. VOLTA'S EXPERIMENTS

4.2.1. *The Pile*

Materials: Zinc and copper squares with a side of 4 cm or larger, paper towel, diluted sulfuric acid or lemon juice, multimeter, a small 25 mA bulb, wire leads with alligator clips, a plastic cup.

Procedure: Cut pieces of a paper towel slightly smaller than the metal squares, moisten it with water squeezing the extra liquid out, make a pile of 30 couples: Zn, paper, Cu, Zn, paper, Cu, etc. Attach the leads to the ends of the pile and grasp them firmly with fingers of both hands previously well moistened. If the shock is not felt, immerse the leads into two cups with water and put the fingers into the cups.

Touch the leads to the tip and the back of your tongue: you should feel a sour taste. Touch the leads to the tongue and the upper gum: you shall see a flash of light (close the eyes). While doing physiological experiments, you can start with connecting one wire to an intermediate plate rather than the end plate and gradually increase the number of couples in the circuit (5, 10, etc.)

Measure the voltage across the pile and the current. Calculate the resistance. Try to light a small bulb.

Reassemble the pile, replace the paper squares with others moistened with a weak acid. Repeat all experiments and compare the results. Does the choice of a liquid affect the power of a pile?

4.2.2. *The Chain of Cups*

Materials: 30 plastic cups which are large enough to host zinc and copper electrodes, wire leads with alligator clips, multimeter, a small bulb. If possible, make electrodes of the size of 2 cm $\times$ 10 cm; otherwise, use the squares from the previous part.

Procedure: Place a zinc and a copper electrode in each cup, taking care they do not touch one another (use a separator made out of an insulator), fill the cups with

water, and connect the electrodes so that zinc of one cup were connected to copper of the next cup, and so on.

Repeat all the experiments described in the previous part and compare the results. Replace water with the weak acid and repeat the experiments. Does the choice of a liquid affect the power of the battery? Compare to the case of the pile.

4.3. STUDENTS LEARN FROM SCIENTISTS

If a teacher is keen on the investigative experimentation, the story supported by some historical experiments may have a practical importance in teaching students how to go about creating a theory explaining their own investigative experiments. In particular, they learn that as long as a theory is consistent and explain several experiments, it has a right to exist even if it cannot account for other experiments. Here the concept of the "partial truth" is very useful: within the given range of phenomena studied and time spent the "partial truth" is *the* truth, and if future research modifies it, the original conclusion still preserves its validity within the original range. Although both Galvani and Volta believed to have discovered the whole truth, since their theories did not cover all known phenomena, they come under the above stated definition of a "partial truth". And if something was good (in the modern view) for Galvani and Volta, it is good for students too. This means that students should not fear of inventing a false theory in their investigations, provided they take care to make their conclusions sufficiently consistent and based on a sufficient number of experiments.

Naturally, students will find out soon the ambiguity of the word "sufficient": one cannot know in advance how many times to repeat each experiment and how many times to modify it in order to arrive at a "partial truth" that is closer to the correct result rather than a false one. Having learned this from their own experience students will become more critical to the certainty of the results of historical experiments and their validity as arguments in a theoretical debate.

5. Conclusion

Learning about a historical controversy may improve students' understanding of how scientists defend a new theory. While the conclusions drawn here are consistent with other cases not discussed in this paper, teacher is not advised to present them as general: it is better to discuss other cases (at least one) and let students do the generalization. Our analysis is not complete, because the role of "human factors" in a scientific debate is left out. This subject certainly deserves a separate study, however, its absence should not preclude teachers from discussing the impersonal factors, especially because the latter are more relevant to improving students' skills in conducting their own investigative experiments.

Note

[1] The author treats the immersion of the whole hand into water as nothing more than a showmanship.

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